

EXTENSION OF CORONAL STRUCTURE INTO INTERPLANETARY SPACE

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ABSTRACT

The evolution of the solar corona and its imprint on the solar wind is investigated by comparing Ulysses radio occultation measurements of path-integrated electron density and density fluctuations in the heliocentric distance range of 21-32 R. with simultaneous measurements of the solar corona by the HAO Mauna Loa K-coronameter. This comparison is made during the 1995 Ulysses solar conjunction, which is ideally suited for sampling the raylike structures revealed in previous radio occultation measurements since the relative motion of the Ulysses radio path is mainly in a direction transverse to the structures. The most striking features resulting from these measurements include: (1) the approximate preservation of coronal structures observed in the white-light measurements as they extend radially into interplanetary space, the only exception being the narrowing of streamers to stalks prior to their eventual radial expansion, and (2) the extension of plumes in polar coronal holes to 30 R. with their signatures apparently found everywhere in the corona including streamers. The emerging picture of the corona is one in which stalks of streamers, occupying a small fraction of volume in interplanetary space, are superimposed on a background corona distinguished by a plethora of raylike structures. All raylike structures, except for the stalks of streamers, seem to be the source of the fast solar wind.

INTRODUCTION

The evolution of the solar corona observed in white-light measurements and its connection to the solar wind measured by interplanetary spacecraft is one of the most important topics of research in inner heliospheric physics. Progress has been slow not only because of the large distances separating solar wind measurements from the corona [Schwenn, 1990; Gosling et al., 1995], but also because of the difficulty within situ solar wind measurements in discriminating between temporal and spatial variations. Recent progress in our understanding of the relationship between the diverse radio occultation measurements [Woo, 1996a; Woo and Habbal, 1997], as well as their relationship to coronal structures [Woo et al., 1995; Woo 1996b] and in situ plasma measurements [Huddleston et al., 1995] has demonstrated that occultation measurements serve as a natural and invaluable bridge between solar and near-Sun interplanetary measurements.

In this paper, we compare ranging (path-integrated density) and Doppler scintillation (small-scale path-integrated density fluctuations) measurements conducted by Ulysses during its 1995 solar conjunction [Pätzold et al., 1995] with Thomson-scattered white-light coronagraph measurements made by the HAO Mauna Loa K-coronameter [Fisher et al., 1981]. The 1995 conjunction is particularly attractive because the Ulysses radio path traversed the plane of the sky from south solar pole to heliographic equator west of the Sun in the heliocentric distance range of 21–32 R. (see Fig. 1a). Hence, unlike in the 1991 Ulysses conjunction, during which streamers and plumes were revealed as they rotated with the Sun in a direction roughly parallel to the radio path [Woo et al., 1995; Woo, 1996b], the radio path intercepts the structures in a transverse direction in the 1995 conjunction. The wide range of latitudes covered by the Ulysses ranging measurements is also more favorable for comparison with the Mauna Loa white-light measurements. Since the longitudinal resolution is directly related to the temporal resolution, which is relatively poor, the spatial resolution of the white-light measurements is higher in latitude than in longitude.

The purpose of this paper is to present the first results obtained from a comparison of simultaneous radio occultation and white-light measurements showing how the spatial structure of the corona evolves and extends into interplanetary space,

1995 ULYSSES RADIO OCCULTATION MEASUREMENTS

Shown in Fig. 2a is the HAO Mauna Loa Observatory Mk 111 K-coronameter synoptic map (courtesy of J. Burkepile at HAO) based on polarized brightness pB measurements made on the west limb at 1.36 R. and covering the relevant portions of Barrington rotations 1892 and 1893. The closest approach points of the Ulysses radio path have been mapped back to the Sun and are displayed on the synoptic map. Ranging measurements averaged over 30-min intervals, normalized to their values at 25 R. assuming a radial dependence of $1/R^2$ for electron density, are displayed in Fig. 2b; the time history is shown in reverse time order and approximately aligned with the corresponding approach points in Fig. 2a. Comparison of Figs. 2a and 2b shows that ranging measurements of the solar wind at 21-32 R. surprisingly mimic the structure of the inner corona observed in white-light, indicating that structure in the inner corona is roughly preserved as it extends radially into interplanetary space.

Further insight into the relationship between the inner corona and the solar wind is obtained by comparing the radio measurements with the daily HAO K-coronameter images. These images are averaged daily around 1800 UT. A typical example corresponding to day of year (DOY) 56 is shown in Fig. 1b. Structures with abrupt boundaries such as polar plumes are more evident in white-light images that have been processed to enhance features which are smaller than 10° in azimuth. Polar plumes are clearly evident in Fig. 1c, which is the edge-enhanced version of Fig. 1b, kindly provided by A. Lecinski and J. Burkepile of HAO, and obtained by subtracting a 10° azimuthal average from the same image.

Since radio occultation only probes a point in the plane of the sky, as apparent from Fig. 1a, the ranging measurements need to be compared with changing daily white-light

images as the Ulysses radio path traverses the plane of the sky, Based on the characteristic signature of plumes observed in earlier ranging measurements [Woo 1996c], three polar plumes, numbered 1-3 in the latitudinal range of S70W-S90W, have been detected in the ranging measurements of Fig. 2b during the interval of DOY 55–59, These plumes are observed in the same latitudinal range of the white-light images during DOY 55–59, as illustrated in the image of DOY 56 in Fig. 1 c showing the three correspondingly numbered plumes,

The time history in Fig. 2b has been converted to a polar plot and superimposed in red on the daily edge-enhanced white-light images for DOY 59, 63, 67 and 68 displayed in Fig. 3. The four daily images correspond to the days on which the four features identified as A-D in Fig. 2b were observed. The location of these features in the plane of the sky are marked by the yellow radial lines on the corresponding daily images.

Shown in Fig. 2c is the time history of 3-rein rms Doppler scintillation which represents small-scale structure or turbulence in the solar wind, Doppler scintillation is low everywhere in the solar wind except in coronal streamer stalks, as found in earlier studies [Woo et al., 1995]. Hence, feature C observed on DOY 67 corresponds to the stalk of the streamer located to the south of the solar wind region probed by Ulysses. Since it is pointing in a northerly direction in the inner corona, it intercepts the Ulysses radio path beyond the field of view of the K-coronameter near $25 R_{\odot}$. Scintillation enhancements can also represent the passage of coronal mass ejections. None were detected by the white-light measurements on DOY 67.

Fig. 2c illustrates the result first noted with Pioneer Venus Doppler scintillation measurements [Woo and Gazis, 1993], that small-scale structures and turbulence are low in the low-density fast wind. Because both density and relative density fluctuations increase significantly in the stalks of coronal streamers [Woo et al., 1995], the conspicuous peak in scintillation caused by the enhanced fine-scale structure in coronal streamers not only

serves as a fiduciary for identifying the streamer stalk, but also as a means for distinguishing streamers from plumes.

That the structure of the inner corona observed in white-light is preserved in interplanetary space as the solar wind flows outward is strikingly demonstrated in the white-light images of Fig. 3. Features A and B represent the southern boundaries of coronal streamers, while feature D is a null in the streamer belt. At least two more plumes (numbered 4 and 5) are evident in Fig. 2b. These plumes clearly overlie the southern most streamer on the west limb shown in the white-light picture of DOY 59. Apparently, they are not seen in the white light picture because the streamer dominates the inner corona.

SUMMARY AND IMPLICATIONS FOR THE SOLAR WIND

Comparison of ranging and Doppler scintillation measurements at 30 R. — in an occultation geometry in which the radio path scans coronal structures in a direction transverse to them — with simultaneous white-light images below $2 R_{\odot}$, shows how coronal structures project radially outwards into interplanetary space. The radio measurements provide evidence for the narrowing of streamers into stalks and their subsequent radial extension farther away from the Sun. They also show how raylike structures, commonly known as polar plumes, appear to permeate the corona, dominating polar and equatorial coronal holes, as well as coexisting with coronal streamers. The radio observations thus unambiguously demonstrate that the imprint of these raylike structures frequently seen in eclipse images of the Sun [e.g., Koutchmy, 1977] fill the corona as they extend into interplanetary space. Such an image provides a natural interpretation of the recent SOHO white light (LASCO) and ultraviolet (UVCS) observations of the extended corona.

This new view of the extended corona has interesting implications for the solar wind. The radial preservation of the boundary between the polar coronal hole and streamer (feature A in Figs. 2 and 3), together with the radial expansion of all structures including

the finest [Woo, 1996a] in polar coronal holes, imply that the solar wind expands radially from polar coronal holes rather than undergoing any significant expansion, as previously thought [e.g., Munro and Jackson, 1977]. This is consistent with recent solar wind models which show that the primary factor in the rapid acceleration of the fast solar wind does not derive from the divergence of the flow tubes, but rather from localized heating in the inner corona [e.g., Habbal et al., 1995; Hansteen, 1996]. In fact, this is also how Parker [1958] first modeled the solar wind. Additional hints come from the fact that in situ measurements show no observational evidence for any difference between the fast solar wind emanating from polar and equatorial coronal holes, even though the boundaries of the two, as inferred from disk and limb observations, suggest a difference in the divergence of the magnetic field lines that seemingly define their boundaries.

Close inspection of the in situ Ulysses observations away from the streamer belt (within $\pm 20^\circ$ latitude) provides additional support for this view (see Figure 1 of Phillips et al. 1995). Taking latitudes north of 20° as an example, it is clear that the flow speed rises very slightly from 700 to 800 km/s between 20° to 80° , while the density decreases in that interval. The profiles of both density and flow speed flatten at 60° , corresponding to the “radial” boundaries of the north polar coronal hole [Gosling et al., 1995]. These observations together with the results presented above suggest that the fastest solar wind comes strictly from the polar coronal holes as defined by their radial boundaries. The radial structures filling the space between these boundaries and the stalks of the streamers, typically known as the quiet Sun, are also the source of the fast solar wind. Additional clues that the wind from coronal holes and the quiet Sun are similar are found in the fact that there is little difference in the small-scale density fluctuations observed by Doppler scintillation for these two types of wind (see Fig. 2c).

In conclusion, the emerging picture of the corona is one in which streamers occupying a small fraction of volume in interplanetary space are superimposed on a background corona consisting of a plethora of raylike structures. It is only in path-integrated

measurements of the inner corona, such as white light, that the coronal streamers give the impression that they dominate the corona. At larger heliocentric distances this dominance drops rapidly, and what remains is the imprint of the raylike structures and the stalks of streamers. All raylike structures, except for the stalks of streamers, seem to be the source of the fast solar wind,

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FIGURE CAPTIONS

Fig. 1 (a) View of Ulysses radio path as seen from Earth during the 1995 solar conjunction (reproduced from Pätzold et al., 1995), (b) daily image for DOY 56 from the HAO Mauna Loa Solar Observatory Mk 111 K-coronameter, (c) the edge-enhanced version of the image in (b) revealing polar plumes.

Fig. 2 (a) HAO Mauna Loa Solar Observatory Mk 11 I K-coronameter synoptic map based on west limb measurements and covering portions of Barrington rotations 1892 (CL 00-1 00°) and 1893 (CL 1800-3600), (b) time history of 30-min ranging in hexems ($101 \text{ }^6 \text{ electrons/n} \sim 2$) measured by Ulysses and normalized to $25 R_{\odot}$, and (c) time history of 3-min rms Doppler scintillation measured by Ulysses and normalized to $25 R_{\odot}$. The features A–D are discussed in the text.

Fig. 3 Normalized ranging measurements by Ulysses (red curve) superimposed on edge-enhanced versions of the daily images from the HAO Mauna Loa Solar Observatory Mk 111 K-coronameter for (a) DOY 59, (b) DOY 63, (c) DOY 67, and (d) DOY 68. The yellow radial lines indicate the locations of the features A–D identified in Fig. 2.

ULYSSES SOLAR CONJUNCTION 995





